SeaWinds on QuikSCAT: Postlaunch Calibration and Validation

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Abstract — The SeaWinds scatterometer was successfully launched aboard the QuikSCAT platform on June 19, 1999. It was designed to accurately determine the speed and direction of ocean surface winds via measurements of the normalized radar cross section, σ_0. Since the retrieved wind vector accuracy depends heavily upon the σ_0 measurement accuracy, the SeaWinds instrument has undergone extensive prelaunch and postlaunch calibration. The postlaunch verification and calibration effort included assessments of instrument functionality and stability, hardware component characterization, data processing algorithm validation, calibration table development, and σ_0 calibration. The achieved accuracy of σ_0 makes SeaWinds on QuikSCAT well suited for a variety of scientific applications over ocean, land, and ice. We outline the postlaunch calibration approach and indicate the expected accuracy of SeaWinds on QuikSCAT σ_0 measurements. We focus predominantly on the use of distributed Earth targets, both for addressing the critical issue of spacecraft pointing and for achieving calibration consistency between the backscatter measurements made by SeaWinds' two antenna beams.

INTRODUCTION

Scatterometers are instruments that accurately measure the normalized radar cross section (σ_0) of the earth's surface. One of the primary applications of scatterometry is to determine the speed and direction of winds over the ocean via an empirically derived model function that relates σ_0 to wind vectors [1]. In order to obtain accurate wind vectors, it is essential that a scatterometer be extremely well calibrated [2].

The SeaWinds scatterometer [3] was successfully launched into earth orbit aboard the QuikSCAT platform on June 19, 1999. It has since undergone an extensive postlaunch calibration using internal calibration mechanisms as well as distributed target analyses.

CALIBRATION PHILOSPHY AND APPROACH

As evidenced by the name "QuikSCAT," great emphasis was placed on reducing the duration of the calibration period so that a credible wind product could be released to the science team as soon as possible. An aggressive calibration campaign was planned and extensive effort was spent on the prelaunch development of postlaunch calibration techniques and software. Departing slightly from our traditional reliance on prelaunch calibration, we were prepared to estimate and apply postlaunch corrections to the instrument calibration without knowing the source of the errors. In other words, our philosophy was to calibrate first and determine the source of calibration errors later. Possible error sources were suggested prior to launch and the software changes necessary to accommodate calibration corrections were incorporated into the ground data processor.

The on-orbit calibration can be divided into two major phases:

1. Assure the safety, functionality, and stability of the instrument system (including the science data processing system).
2. Calibrate σ_0.

SAFETY, FUNTIONALITY, AND STABILITY

As soon as the instrument was turned on, its safety and functionality were monitored. Error flags were checked and temperatures were examined to make sure that the instrument was not in any danger. Functionally, the instrument performed excellently: commands were received and processed correctly, onboard algorithms operated as designed, and parameters remained within their allowable limits.

After the instrument was determined to be safe and functional, we began examining its performance parameters for stability. This task was critical since many of our rapid calibration schemes required the spacecraft and instrument to be stable. Instrument parameters such as the transmit power, receiver gain, and receiver temperature were monitored and their stability confirmed.

The ground data processor was also validated both pre- and postlaunch to assure the correct calculation of all parameters necessary for the calculate of σ_0.

σ_0 CALIBRATION

Once the stability of the instrument and spacecraft were verified, we focused on the accurate calibration of σ_0. Due to processing constraints, the calculation of σ_0 for SeaWinds is

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partially pre-computed and stored in a table. The radar equation used is:

$$\sigma_0 = \frac{E_s}{X_{cal} X_{int}} \quad (1)$$

where E_s is an estimate of the echo signal energy, X_{cal} is a calibration term derived from instrument internal loopback calibration measurements, and X_{int} is a pre-computed integral which was parameterized as a function of the echo baseband frequency. The equations are for X_{cal} and X_{int} are:

$$X_{cal} = \frac{\lambda^2 G_p^2}{(4\pi)^3} \frac{P_t G_r}{L} \quad (2)$$

where λ is the wavelength, G_p is the processor gain, P_t is the transmit power, G_r is the receiver gain, and L is the sum of the instrument losses, and

$$X_{int} = \int \frac{G_{at}(\theta,\phi) G_{ar}(\theta,\phi) F(f)}{R^4} dA \quad (3)$$

where, θ and ϕ are the antenna look and azimuth angles respectively, G_{at} is the antenna gain for the transmit event, G_{ar} is the antenna gain for the receive event, F(f) is the filter response as a function of baseband frequency, R is the slant range from the instrument to the target, and the integral is performed over area on the earth, A.

The majority of σ_0 calibration involved verifying the value of X_{cal} and calibrating X_{int} using distributed earth targets. In the next two sections, we focus on the calibration of X_{int}.

ATTITUDE ESTIMATION

In order to understand the importance of spacecraft attitude, it is helpful to understand the SeaWinds instrument design. The SeaWinds scatterometer uses range compression techniques to transform range into frequency [4]. By digitally filtering the echo, we can divide each measurement footprint into multiple pieces, known as slices. Each slice has its own echo energy measurement corresponding to a given portion of the antenna footprint. By using range compression, we obtain multiple echo energy measurements across each antenna footprint.

The antenna pattern has a large affect on the measured echo energy for a slice. Slices which are near the peak two-way gain of the antenna pattern tend to have larger measured energies than those which are further down on the antenna pattern. When calculating σ_0, the effect of the antenna pattern is compensated for by X_{int}. Errors in the value of X_{int} used to calculate σ_0 for a slice will translate into errors in the calculated σ_0 for that slice. Our calibration goal is to make the value of X_{int} used in the σ_0 calculation equal to the true value of X_{int}.

One of the things that can affect the value of X_{int} is the spacecraft attitude. For example, if the spacecraft is rolled without our knowing it, the antenna pattern will not be exactly where we think it is. Thus, the values of X_{int} that we use to calculate the slice σ_0's will be incorrect.

The relative magnitudes of slice energies can be predicted by knowing the values of X_{int} for each slice and employing some simple assumptions about the target σ_0's. Once the predicted slice magnitude profile is determined, it is straightforward to calculate a predicted peak frequency by fitting a Gaussian to the slice magnitudes. At this point, we know where we should expect the maximum return signal.

Similarly, if we fit a Gaussian to the measured echo energies, we can determine the location of the actual peak of the return signal. If the measured peak does not align with the predicted peak, we assume that there is an error in our calculation of X_{int} arising from a knowledge error in the spacecraft attitude. We can then search through spacecraft attitude biases to find the one which minimizes the differences between the measured and the predicted peaks.

This technique was applied to estimate the effective roll and pitch biases of the QuikSCAT spacecraft. The estimated biases were then applied to the spacecraft attitude system to maintain geodetic pointing of the SeaWinds antenna. After making these attitude changes to the spacecraft, the resulting attitude biases were re-estimated and determined to be extremely small. Table 1 shows the estimated roll and pitch biases for both the original spacecraft attitude and for the adjusted spacecraft attitude. The SeaWinds instrument is not very sensitive to yaw and our yaw estimate of approximately 0.03° was not applied to the spacecraft.

Table 1 . Estimated roll and pitch biases

Attitude Parameter	Before Adjustment	After Adjustment
Roll Bias	-0.0886°	0.0009°
Pitch Bias	-0.1243°	-0.0018°

Two days worth of scatterometer data were used to perform the attitude estimation. A spacecraft attitude bias was estimated for each orbit step (1/256th of an orbit). A plot of the estimated pitch bias versus orbit step, after the adjustment was made, is shown in Fig. 1. This technique was applied over ocean only, so the gaps around orbit steps 64 and 192 correspond to the north and south poles respectively. Note that there is very little variation from orbit step to orbit step, indicating the stability of the spacecraft attitude.

BEAM, AZIMUTH, AND SLICE BALANCING

We divided the remaining σ_0 calibration into three key parts: beam balancing, azimuth balancing, and slice balancing. The object of beam balancing is to remove any beam biases relative to the geophysical model function. In other words,

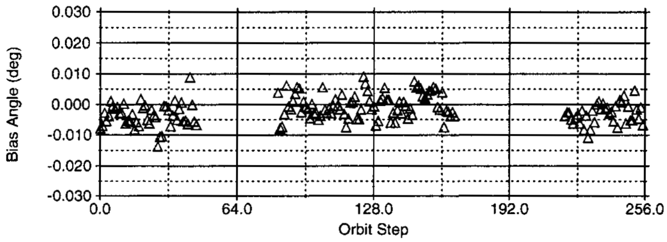

Fig. 1. Pitch bias versus orbit step

the object is to adjust the antenna gains used in the calculation of σ_0 such that the measurements from both beams, on average, agree with the model function. This task was performed by the SeaWinds on QuikSCAT science working team and the results are shown in Table 2.

Table 2. Beam balance

Beam	Prelaunch Antenna Gain (dB)	Adjusted Antenna Gain (dB)
Inner	39.5	38.42
Outer	40.9	40.385

The object of azimuth balancing is to remove any antenna azimuth dependant biases in σ_0 such that if the instrument were to measure a uniform, isotropic surface, the measured σ_0 would be identical, independent of the antenna azimuth. This task was also performed by the science working team. The conclusion was that the azimuth imbalance was less than 0.1 dB and therefore no azimuth correction was made.

Slice balancing is performed to insure that the slice σ_0's yield "consistent" results relative to the full-footprint measurements. This is done by calculating the ratio of the slice σ_0 for a given scene to the full-footprint σ_0 for the same scene and averaging a large number of measurements. Because the incidence angles for the slice measurements are in general different than that for the full-footprint, a correction must be made for the variation of σ_0 with incidence angle for the specific scene being examined. To perform this slice balancing procedure, either the ocean surface or a suitably uniform land surface may be used. Fig. 2 shows the slice imbalance for the center eight slices from the QuikSCAT inner beam when an ocean target is employed. The plotted curves show the σ_0 difference between each slice and the full-footprint. Here approximately 300 orbits worth of data have been averaged to calculate the slice imbalance as a function of scan azimuth angle. In general, the slices farther down on the antenna pattern had a larger slice imbalance, but the amount of correction applied was still a maximum of about 0.5 dB. The QuikSCAT data has been corrected for this by adjusting the table of X_{int} values, and the current residual slice balance error is estimated to be < 0.2 dB.

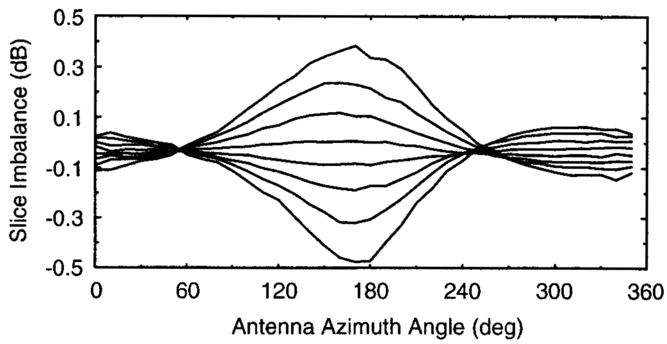

Fig. 2. Inner beam slice imbalance prior to correction

EXPECTED ACCURACY

We estimate the relative σ_0 accuracy of full-footprint measurements to be 0.1 dB 1σ. We estimate the slice σ_0 accuracy relative to the full-footprint σ_0 to be < 0.2 dB 1σ for all 8 slices. The QuikSCAT spacecraft exhibits excellent attitude control and knowledge and this has contributed to our high σ_0 calibration accuracy.

CONCLUSIONS

The calibration of QuikSCAT involved a different philosophy than the calibration of previous scatterometers. The calibration team was prepared to correct σ_0 in absence of knowing the cause of calibration errors. As long as the instrument calibration was stable, it was applied. The result was a quickly calibrated instrument with high accuracy σ_0 measurements.

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